

MEASUREMENT OF DEEP OCEAN CURRENTS WITH ONE-SHOT  
NEUTRALLY BUOYANT FLOATS

by

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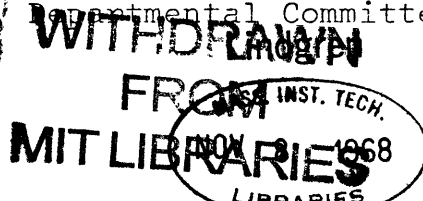
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ABSTRACT

A method of measuring deep ocean currents is proposed, utilizing many one-shot explosive neutrally buoyant floats. These floats, which explode after a preset time in the water, may be located over long distances by making use of the oceanic sound channel. The useful data will consist of the mean drift for some depth range, the variance with respect to the mean drift, and a possible correlation between vertical and horizontal scatter.

There are to be 20 floats deployed in a cluster around 1000 meters deep. Each float will telemeter its depth to a surface ship immediately after deployment. The floats will explode after several weeks, and the explosions will be located by hyperbolic navigation in the sound channel.

This report concerns primarily the developmental aspect of the system, including the detailed design of the floats. The units were designed under severe cost restrictions.

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## CHAPTER I. INTRODUCTION

### A. Description of the Project

This introduction will be a general description of the proposed thesis, and a brief discussion of its results. All the topics mentioned in this section will be discussed in more detail in the following chapters.

The central problem which this thesis is intended to attack is that of measuring deep ocean currents, especially slow drifts. A major difficulty in measuring slow currents is that superimposed upon the mean drift are several forms of noise (inertial oscillations and tidal oscillations, for example). Slow drifts generally cannot be measured with instruments lowered from a ship, due to the motion of the ship, and moored instruments have proven to be very expensive and cumbersome to use, particularly in deep water. For these reasons, free floating instruments have been commonly used to measure deep currents.

The most common form of free-floating deep current probe is a neutrally-buoyant float, known as a Swallow float.<sup>1</sup> Its neutral buoyancy is a result of its incompressibility relative to sea water, and of careful ballasting. Such a float is equipped with an acoustic sound source (a "pinger") to enable a surface ship to follow the float as it drifts.

Only a few floats can be tracked simultaneously by this method. If the deep currents were steady and deterministic, the number of floats would not matter much. However, the presence of the inertial currents (which are due to the earth's rotation), whose velocities may be large compared to the slow

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<sup>1</sup>J.C. Swallow, "A Neutral-Buoyancy Float for Measuring Deep Current". DSR, Vol. 3, pp. 74-81, 1955.

mean drift, and the tidal currents, make the Lagrangian estimate of the mean drift inaccurate. Therefore a measurement technique with sufficient statistical reliability is necessary, that is, one which obtains a meaningful average through the use of many floats. Furthermore the expense involved in the use of a ship for extended periods of time is very great.

The acoustic properties of the deep sound channel provide a means for overcoming the foregoing difficulties, by making possible the tracking of many Swallow floats over long distances without the use of a ship. The sound channel is characterized by a sound velocity minimum which occurs at some depth throughout most of the world ocean. In the North Atlantic, in the region of Bermuda for example, the depth of minimum sound velocity is found to be approximately 1,200 meters. Clearly, sound energy originating at or near this depth will be partially trapped by refraction, and "channeled" horizontally over great distances. In other words, for a unidirectional source, the spreading becomes essentially cylindrical instead of spherical, with correspondingly less attenuation.

Sudden sharp noises in the sound channel, such as explosions, can be accurately located if the sound can be heard. Hyperbolic navigation can be used to determine both the time and the place of an explosion, if the sound can be heard and timed from three or more hydrophones in the sound channel. Indeed, it is the existence of such hydrophones around the West Indies (U.S. Air Force, Atlantic M.I.L.S. System), that makes this effort possible.

With this background, the project may now be described. It was proposed that twenty Swallow floats be deployed simultaneously in some convenient region of the ocean, at or near the sound channel depth. These floats would drift silently for some predetermined time, then explode. Each explosion would be recorded from the M.I.L.S. hydrophones, and the position and time

of explosion calculated. The net drift of each float between the time of deployment and explosion would then be known.

The advantages of this proposal are threefold. First, the large number of floats improves the degree of statistical reliability in the calculation of the mean drift; secondly, the floats may be located over great distances (thousands of kilometers) which implies longer drift times than were possible with the old technique; and thirdly, ship time is not necessary except for deployment.

Many oceanographic experiments have demonstrated that in the oceans a significant vertical microstructure exists, with stratification occurring over vertical distances as small as a few meters. Evidence indicates that the deep currents also move in horizontal sheets. One might therefore expect that the variance of a float's motion with respect to the mean motion would correlate with its vertical separation from the nominal depth.

To test the significance of this possibility a refinement of the experiment was proposed. The depth of each float at the time of deployment would be telemetered back to the surface ship, and the final explosions would be timed accurately enough that each explosion could be identified as coming from a particular unit. Thus the experiment would measure how well a single Lagrangian sensor actually represents the motion of a large parcel of water.

It will be evident at this point that this thesis has a dual objective. It is an oceanographic experiment of a rather statistical nature, and it is also a developmental project. The system which is to be the result of this work will of course be useful in many future oceanographic studies.

The idea of using the sound channel to track Swallow floats was the germinating agent for this project. Thus the developmental aspect of the project involved finding a suitable method of using the sound channel. The

use of an explosive, the design of the float, the electronics, and the details of deployment, all had to be evolved under the requirements of cost, reliability, and safety. The cost requirement was in fact quite extreme; due to the limited funds available, the unit cost was originally proposed to be \$125. The safety requirement could not be compromised, however, since there is no room for error when dealing with high explosives!



B. The Results

The reader will no doubt realize that this project, involving both development "from scratch" and a significant oceanographic experiment, might take a rather long time to complete. The original proposal called for both phases to be included in the thesis , but it was recognized at that time that the actual thesis report might have to be confined to merely the developmental aspect (the project itself has a life of its own and will be completed independent of the thesis report).

This state of affairs has indeed come to pass. The developmental work has proceeded well, if slowly, and has been brought to a satisfactory conclusion. The actual construction and deployment of the twenty units, however, is still continuing.

Laboratory tests have been conducted upon two completed units, with good results, and one unit was deployed near Bermuda in a full-scale test. Unfortunately, this test unit vanished into the depths and was never heard from. An additional sea test at the same time verified that the explosive mechanism itself functions well. All the test results, and all the available information concerning the lost unit, will be discussed in later chapters of this report.

## CHAPTER II. DEEP OCEAN CURRENTS - THE NATURE OF THE PROBLEM

This chapter will summarize those aspects of deep ocean currents which are relevant to this project. In particular, this chapter must clearly point out the difficulties involved in the measurement of ocean currents and the major sources of measurement error.

We will limit our attention to those areas of the oceans where we do not expect to find major wind-driven currents. This project is concerned with the deep slow drift of large masses of water, and the problems involved in the measurement of such drifts are rather different from the problems of measuring fast currents. Hence the limitation is not arbitrary.

Neither is it the purpose of this thesis to speculate upon the causes of deep drift currents, except insofar as such speculation may assist in the design of the experiment.

### A. General Structure of Middle-Latitude Oceans

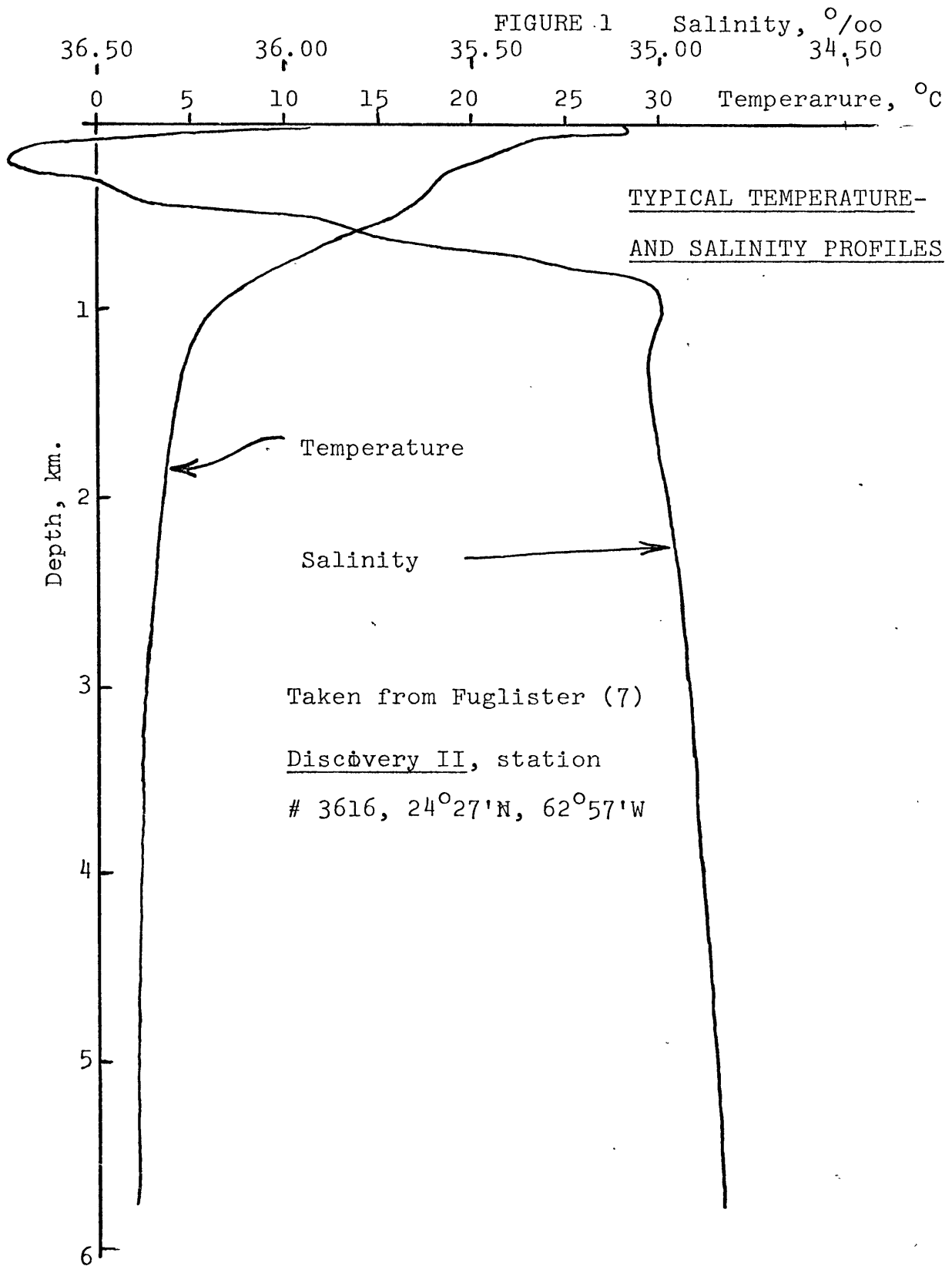
Figure 1, page 11, is a temperature and salinity profile<sup>1</sup> of a typical "quiet" region of the ocean, in this case in the Sargasso Sea area near Bermuda. This distribution of temperature and salinity is found to change very little over time.<sup>2</sup> Below the main thermocline the temperature and salinity are extremely stable.

The currents below the main thermocline should be characterized by the slow drift of the thermocline<sup>haline</sup> circulation. In particular, in the area around

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<sup>1</sup>F.C. Fuglister, Atlantic Ocean Atlas, Woods Hole Oceanographic Institution, Vol. 1, 1960.

<sup>2</sup>Schroeder, Stommel, Menzel, and Sutcliffe, "Climatic Stability of 18° Water at Bermuda", JGR 64(3), pp. 363-366, 1959.



Bermuda ( $30^{\circ}\text{N}$ ), Defant<sup>3</sup> and others describe a southward-trending current whose depth ranges from the base of the main thermocline (800-900 meters) down to several kilometers. The velocity of this current is apparently poorly known, except that it should be small, perhaps of the order of 1 or 2 centimeters per second. In its gross features, this motion is thought of as being uniform over distances of many hundreds of kilometers horizontally, and many hundreds of meters vertically.

The existence of this drift has been inferred from many sources of indirect evidence, such as Wüst's "core method"<sup>4</sup> of tracing the spreading of water masses. The few existing direct current measurements, particularly those made by the neutrally-buoyant Swallow float method<sup>5</sup>, have tended to confirm the indirect evidence, although the variability of these deep currents is quite remarkable. Experiments such as those done by J. Crease<sup>6</sup> for example, show that the deep currents can have a surprisingly large velocity (of the order of 10 centimeters per second at 2000 and 4000 meters) as well as a lack of directional stability. Other experiments, such as those of Pochapsky<sup>7</sup> near Bermuda, show a net southward drift of a few centimeters per second embedded in a "noisy" current microstructure, which appears to be due primarily to internal waves of inertial period. These will be discussed below.

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<sup>3</sup>A. Defant, Physical Oceanography, Vol. 1, Pergamon Press, N.Y., 1961, p. 695.

<sup>4</sup>Ibid., p. 690.

<sup>5</sup>J.C. Swallow, op. cit.

<sup>6</sup>J. Crease, "Velocity Measurements in the Deep Water of the Western North Atlantic", JGR, Vol. 67, #8, pp. 3173-3176, 1962.

<sup>7</sup>T.E. Pochapsky, "Measurements of Small Scale Oceanic Motions with Neutrally-Buoyant Floats", Tellus, Vol. 15, pp. 352-362, 1963.

## B. Inertial Oscillations

One of the simpler solutions to the linearized equations of motion of a frictionless fluid is a current of constant speed. In a non-rotating system without boundaries such a current will move in a straight line as a result of its own inertia; but in a rotating reference frame such a current will move in a circle (an "inertia circle") due to the action of the Coriolis force. The period of the circular oscillation will be

$$T_p = \frac{\pi}{w \sin \phi} = \frac{1}{2} \text{ pendulum day}$$

where  $w$  is the angular velocity of the earth, and  $\phi$  is the latitude. The radius of the inertia circle depends upon the speed (denoted " $c$ ")<sup>8</sup>:

$$r = \frac{c}{2 w \sin \phi}$$

Inertial currents have been frequently observed in the oceans at great depths. For example, J.A. Knauss<sup>9</sup>, working in the Pacific Ocean at about 30°N latitude, discovered inertial oscillations at 1000 meters depth whose radius was about 1.5 kilometers, and whose maximum current was 18 centimeters per second.

Knauss's results also illustrated several other phenomena associated with deep inertial currents. First, the amplitude of the oscillations decreased over a period of several days, most probably due to friction, which decreases the speed  $c$ , and hence the radius of the oscillation,  $r$ . Thus the amplitude of this noise process is not constant. Secondly, Knauss found that the phase of the inertia oscillations varied with depth. This

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<sup>8</sup>A. Defant, 1961, op. cit., p. 441 ff.

<sup>9</sup>J.A. Knauss, "Observations of Internal Waves of Tidal Period made with Neutrally-Buoyant Floats", JMR, Vol. 20, #2, pp. 111-118, 1962.

result was also found by Pochapsky<sup>10</sup> near Bermuda, and by Defant in an analysis of an "Altair" anchor station in the north Atlantic<sup>11</sup>; Defant theorizes that

"these phase changes which are related to the oceanographic structure at this station indicate that these inertia oscillations were coupled with internal waves which are the expression of a whole system of inertia oscillations of the surrounding water masses."

Thus in general the phase of the inertial oscillation at any depth may be thought of as a random variable.

The vertical distance scale over which significant phase variations occur is imperfectly known; if the cause of the oscillations is impulsive in nature there may in fact be no single significant scale. For example, Pochapsky (1966)<sup>12</sup>, suggests that turbulence in deep water may be sporadic or violent in randomly localized regions. Such mixing would produce volumes of almost isothermal water which would collapse into thin horizontal planes at the depth of the appropriate density.

The foregoing examples have served to illustrate the nature of the inertial oscillations. The relatively large orbital water velocity and the randomness of phase and amplitude are clearly sources of error in the measurement of slow mean drifts.

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<sup>10</sup>T.E. Pochapsky, "Measurement of Deep Water Movements with Instrumented Neutrally-Buoyant Floats", JGR, Vol. 71, #10, pp. 2491-2504, 1966.

<sup>11</sup>A. Defant, 1961, op. cit., p. 449.

<sup>12</sup>T.E. Pochapsky, 1966, op. cit., p. 2502.

### C. Other Forms of Current Noise

There are several other forms of current noise which may be superimposed on the mean drift. Tidal currents, internal wave motions, and turbulence would appear to be the major contributors.

Tidal currents do exist in the deep sea, although their velocities ought to be small. At latitudes near  $30^{\circ}\text{N}$  and  $30^{\circ}\text{S}$ , however, the diurnal tidal oscillations may be indistinguishable from inertial oscillations, whose period at those latitudes is 24 hours. Some authors, such as Knauss<sup>13</sup>, suggest that the tide-producing forces may couple with the inertial oscillations at  $30^{\circ}$  latitude, producing a resonance. At other latitudes, tidal currents generally appear to be no greater than inertial currents.

Little is apparently known about the horizontal velocities due to internal waves and turbulence in deep water. Short period internal waves ought not to introduce significant current measurement errors, anyway. Long period phenomena may account for observations like Pochapsky's (1966)<sup>14</sup> that two neutrally-buoyant floats which were separated vertically by about 100 meters drifted apart at an average rate of 1 kilometer per day. Clearly, some sort of shear motion with a very long period must have been present, perhaps due to spreading of mixed water masses.

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<sup>13</sup>J. Knauss, op. cit., p. 118.

<sup>14</sup>T.E. Pochapsky, 1966, op. cit., p. 2495.

### CHAPTER III. THE SOUND CHANNEL

The method of current measurement described in this thesis relies heavily upon use of the oceanic sound channel, so much so in fact that the nature of the sound channel must necessarily be discussed first.

#### A. Description of the Sound Channel

Briefly, the sound channel consists of a sound-velocity minimum at some depth in the ocean, which results from the fact that sound velocity is an increasing function of both temperature and pressure. The negative temperature gradient near the surface in middle latitudes has a greater effect on sound velocity than the positive pressure gradient, so that near the surface the sound velocity decreases with depth. At greater depths the increasing pressure predominates, and the sound velocity increases with depth.<sup>1</sup> Thus there exists a sound velocity minimum, which is typically 1200 meters deep. Figure 2, page 17, is a typical sound velocity profile for the North Atlantic.

This deep minimum in sound velocity has a channeling effect on the sound. Sound originating on the axis of the sound channel (i.e., the depth of the minimum) is confined to the channel, and hence its intensity in the channel falls off only as  $1/r$  (cylindrical spreading) rather than as  $1/r^2$  (spherical spreading). This fact, plus the fact that sea water is relatively transparent to acoustic energy, makes possible the transmission of sound over great distances.

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<sup>1</sup>R.A. Frosch, "Underwater Sound: Deep-Ocean Propagation", Science, Vol. 146, pp. 889-894, 1964.



FIGURE 2

TYPICAL SOUND VELOCITY PROFILE

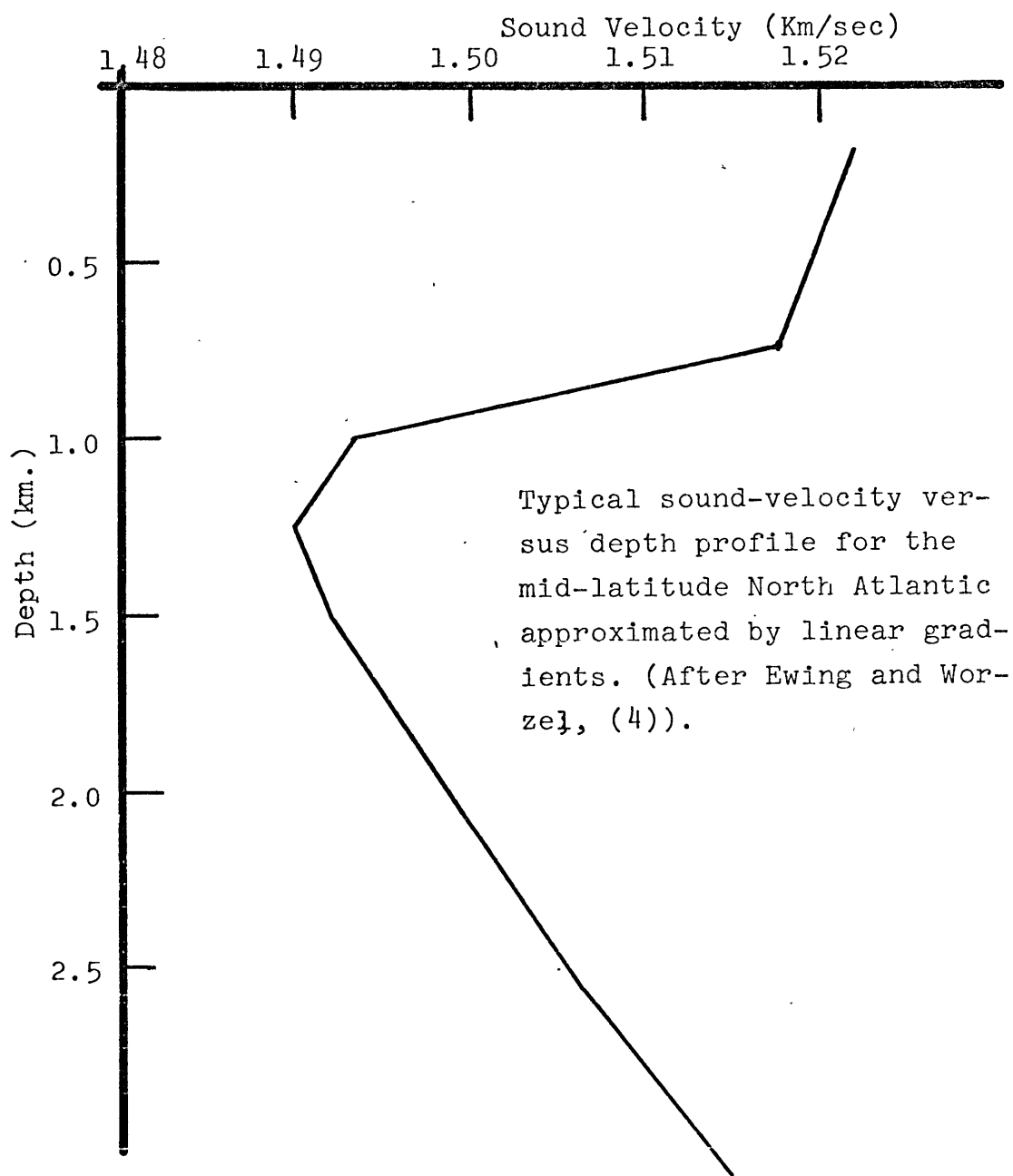
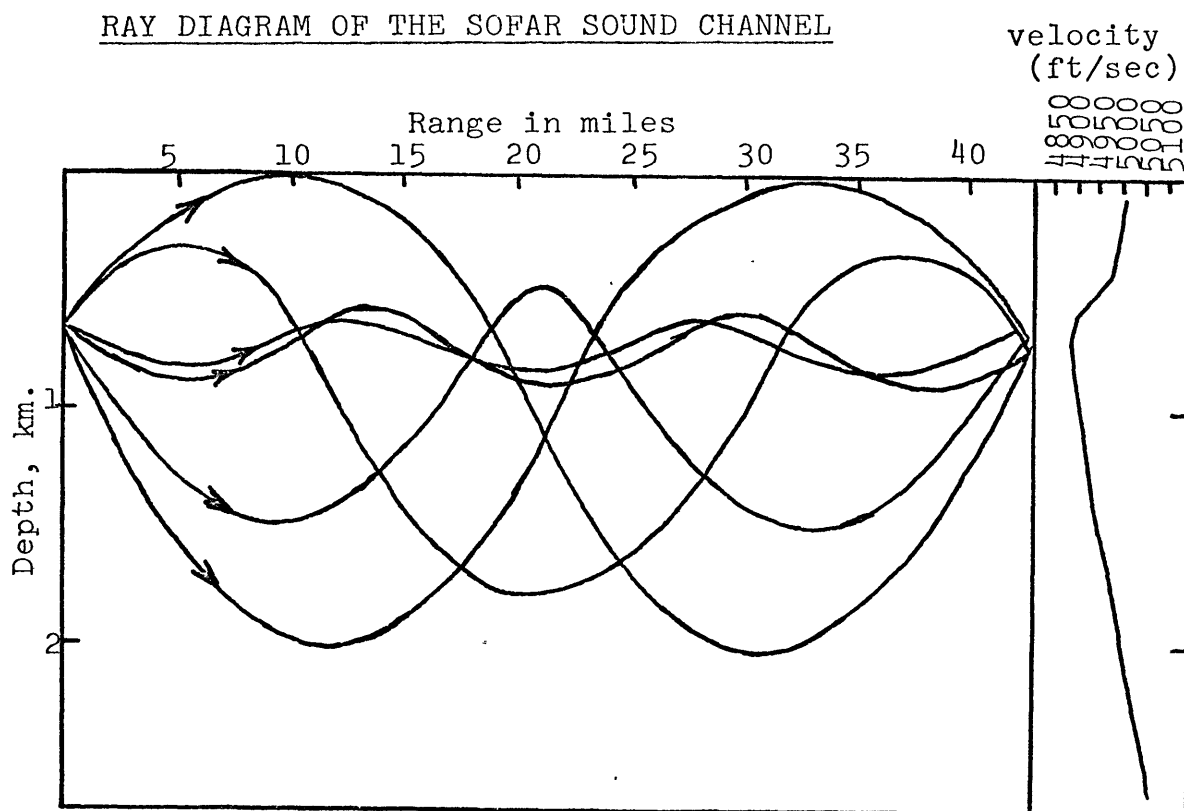


FIGURE 3 (a)

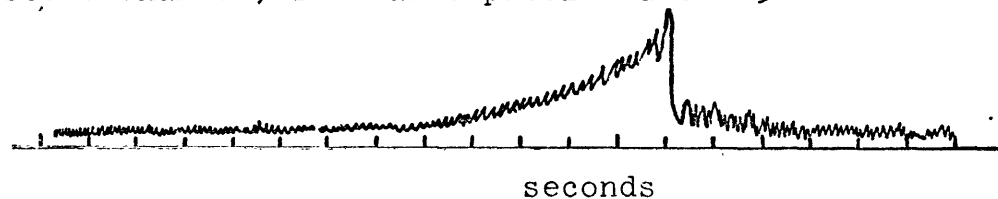


Reproduced from Ewing and Worzel (4).

FIGURE 3 (b)

TYPICAL EXPLOSIVE "SIGNATURE"

This is a typical signature (heard on a hydrophone in the sound channel) from an explosion about 500 n.m. distant.



Reproduced from Bryan, Truchan, and Ewing (1).

## B. Propagation of Explosive Signals

Consider the ideal case of an impulsive sound source on the axis of the sound channel, and a receiver on the axis some distance away. All the acoustic energy within a certain spherical angle will be trapped in the channel, but only certain rays will be heard at the receiver. Figure 3, page 18, is a sketch of the ray paths from the source to the receiver.

With the assistance of Snell's Law the travel time along each ray may be computed. It is found that the rays which make the largest excursions travel fastest, so that in spite of their longer paths, these rays arrive at the receiver first. Last to arrive at the receiver is the sound traveling along the axis of the sound channel.<sup>2</sup>

The energy per unit time at the receiver diverges near the final time, because the number of ray paths which are nearly horizontal is infinite. In actuality, an explosive signal is heard as an increasing crescendo of sound, culminating in a final crash, followed by silence. A typical explosive "signature" is shown in Figure 3b, page 18. The sharply defined arrival time of the axial pulse allows the use of ranging techniques to locate the sound source.

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<sup>2</sup>Ibid., p. 892.

### C. Sound Fixing and Ranging (SOFAR)

The simplest form of sound ranging assumes a constant sound velocity along the axis of the sound channel. Then, if the time of explosion and the time of arrival of the axial pulse at a receiver are known, the range from the explosion to the receiver can be calculated. Thus, if two hydrophones are available, the position of the explosion can be found as the intersection of two range circles.

If the time of explosion is not known precisely enough, the explosion can still be located if three hydrophones are available. In this case the difference in arrival times between pairs of hydrophones is the basic data, and it yields, not a range circle as above, but rather a hyperbola. The source is then located at the intersection of two hyperbolas. On the earth, of course, these curves must all be described in spherical coordinates.

The range over which explosions can be located is quite large. For example, Frosch, Klerer, and Tyson<sup>3</sup> have shown that a charge of one kilogram of TNT can be reliably heard over 2500 nautical miles.

These same small explosions could be located to an accuracy of about 5 miles at that range, using hyperbolic navigation. The accuracy should be considerably better at reduced ranges. The primary limitation on the accuracy is the accuracy to which the sound velocity on the sound channel axis is known. For the region of the Sargasso Sea, where the temperature field is remarkably stable<sup>4</sup>, one would expect the sound velocity to be stable also. Experiments done recently by Dr. H.T. Rossby in the Sargasso Sea have shown that a small sound source can be located to within 3 kilometers over a range of 800 kilometers.

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<sup>3</sup>R.A. Frosch, M. Klerer, and L. Tyson, "Long Range Localization of Small Underwater Charges", JASA, Vol. 33, pp. 1804-1805, 1961.

<sup>4</sup>Schroeder, Stommel, Menzel, and Sutcliffe, 1959, op. cit.

#### CHAPTER IV. METHOD OF ATTACK

For deep and slow currents, whose velocities are typically less than one knot, it is impractical to suspend current probes from a surface ship because the wind drift and wave movement are too great. Therefore currents must be measured by either free-floating or moored probes, or by indirect methods. The only method to be considered in this thesis is the free-floating probe. The central idea around which this project is built is that of using the sound channel to track neutrally-buoyant (Swallow) floats.

In Chapter III the propagation of sound from explosive sources was discussed, and it was concluded that an inexpensive and accurate way of locating objects in the sound channel is to cause them to explode. Therefore the basic device must be an explosive Swallow float, and the basic method of use must be simply to put it in the sound channel at a known time and position and later to calculate its position and time of explosion. Thus the primary data will consist of the net drift of a unit over some period of time.

It is evident that such "one-shot" devices, which provide only one data point each, must be used in large numbers to provide meaningful information. However, one-shot devices must be inexpensive or the idea loses a great deal of its charm. The following chapters will deal with the detailed design of the floats; the remainder of this chapter will deal with the design of the proposed experiment.

In Chapter II it was said that the deep currents very likely move in sheets whose thickness is a few meters or tens of meters. Presumably, the larger water mass (by which we mean a water mass whose vertical extent is measured in hundreds of meters) drifts at some mean rate, which we desire to know. The simplest and most direct experiment is to put a number of floats

in a cluster around some nominal depth, all at the same time and geographical position. Then the floats will presumably scatter horizontally as they drift (due primarily to their vertical separation), and the average of all the individual drift vectors should approximate the mean drift for that depth range. Furthermore, the measured variance of the drift (which is the mean square value of the scatter) is an approximation of the a priori variance of any Swallow float at that depth.

The mean drift approximation has value in itself, as desirable data. However, the variance approximation will be of even greater value because it provides an estimate of the accuracy inherent in any Swallow float experiment. For example, one might later desire to make a synoptic study of the drift over a wide area. The variance data will provide the necessary accuracy limits for the individual floats in the synoptic survey. Thus the simple single-cluster experiment is the basic one upon which all other experiments rest.

Following this line of approach, it is easy to see how much vertical scatter should be allowed. Since no Swallow float will sink to its exact design depth, the way to achieve a representative vertical cluster is simply to ballast all units to the same nominal depth. Then after deployment, the RMS scatter of all the units should approximate the expected deviation of any single float. In this way the measured horizontal variance from the cluster experiment will even more closely approximate the expected horizontal variance of a single float.

A further refinement is actually to measure the depth of each float after deployment. This permits computation of the actual RMS vertical scatter, which is a valuable measure of the accuracy with which a float can be ballasted. Furthermore one might expect some correlation between the vertical deviation of a float from the mean depth and its horizontal deviation

from the mean drift. If so, this data would provide a quantitative handle on the scale of the current microstructure. In the extreme case, of course, knowing the depth of each individual float allows the experimenter to discard anomalous data (i.e., if one float is badly ballasted and is far from correct depth).

Good engineering practice dictates that the number of floats necessary should be carefully calculated from the desired tolerance of the variance measurement. That is, first the experimenter should decide how well the variance ought to be known, and then using all existing information about the currents, calculate the number of degrees of freedom necessary to achieve that accuracy. This is not possible here because the process is not stationary. Furthermore, the actual number of floats to be used in this experiment was dictated by budgetary limits. If the floats could be made as cheaply as \$125, then twenty units was the maximum number, making allowances for possible increase in the cost.

The nominal depth to use for this experiment was not very important, and was in fact suggested by the particular explosive used (see Chapter V). The depth decided upon was 1,000 meters.

The most convenient geographical location was decided to be in the Sargasso Sea area, about midway between Bermuda and Puerto Rico ( $25^{\circ}\text{N}$ ,  $68^{\circ}\text{W}$ ). This location (which is not a critical factor) is the center of the arc of deep hydrophones mentioned in Chapter III, and is therefore optimum for acoustic reception.

Another consideration is that of observation time, that is, how long after deployment should the floats explode? If the deep currents were known to be steady, or at least Wide Sense Stationary, then the optimum observation time would be the maximum allowable subject to distance limits or the like.

Unfortunately the known or suspected presence of huge eddies, planetary waves, seasonal change, etc. make stationarity highly unlikely, at least over a period of months. Since the inertial period at moderate latitudes is of the order of one day, a reasonable compromise would seem to be from several days to several weeks.

In reality very little seems to be known about the extent of temporal variation of the current system; so little in fact that a single mean drift measurement would be of questionable value. Therefore it was deemed necessary to separate the cluster of floats into three sub-clusters, timed to go off at successively greater periods. Of the twenty floats (all ballasted for the same nominal depth), six were planned to explode after approximately one week, six after two weeks, and the remaining eight after three weeks. Thus in essence there are to be three experiments, all starting at the same time, and although each experiment has only about one-third the number of degrees of freedom, this degradation is more than offset by the addition of temporal data. This decision, to split the experiment into three subexperiments, was the most subjective consideration of this project (there exists very little data, and the author's personal prejudice decided the issue).

As mentioned in Chapter II, the additive noise in the form of inertial currents is of known period, but random phase and amplitude. The phase is a random variable (i.e., it is unknown but stable) whereas the amplitude is apparently a random process (it changes with time). This fact allows an intriguing method of reducing the noise: set the explosions to occur an integral number of inertial periods after deployment. This helps to cancel the noise, provided the phase of any local parcel of water does not vary; which is true only if the parcel remains at the same latitude.



It was mentioned earlier in this chapter that each float must be identifiable by the timing of its explosion. Therefore the six or eight floats in a group cannot be set for exactly the same time. Rather, they must explode sequentially, separated in time by at least twice the magnitude of the accuracy of the timer. For example, if the timer were set for 10 days ( $10^6$  seconds) and had an accuracy of 100 seconds in  $10^6$ , then the minimum allowable spacing between successive explosions must be 200 seconds. Clearly the inaccuracy in the timer must be minutes, not hours. Refer to Chapter V for details.

## CHAPTER V. DEVELOPMENT OF THE EXPLOSIVE UNIT

### A. Safety

This explosive Swallow float possesses all the essential features of a time bomb. Like any good time bomb, it must be reliable, accurate, and above all safe. It must be perfectly safe for storage and transport, yet it must be easy and quick to set; once set, it must remain harmless during deployment, and once deployed it must never threaten surface ships or public beaches.

The first question was, how big a bomb was necessary? Since acoustic transmission in the sound channel is unreliable (it fades very much like atmospheric transmission) a good general rule is: the bigger the better. More quantitatively, it has been shown<sup>1</sup>, as mentioned in Chapter III, that in the Atlantic the maximum range of reception of the signal from a 2 1/2 pound charge of high explosive is about 2500 nautical miles. For this project, expected ranges of 1200 miles or less are the maximum, and therefore explosive charges of less than one pound were deemed satisfactory.

The requirement that the bomb be safe on the surface and explode only at great depths suggested the use of a pressure-detonated explosive. The U.S. Navy, upon application, volunteered to supply just such a unit. Designated WHA-1-68 the explosive consists of a main charge of 0.45 pound of Detasheet "c" ("plastique") and an arming and firing mechanism, all enclosed in a protective cover of epoxy and brass. The unit is self-contained, and completely mechanical (no dangerous electrical connections). Furthermore it is highly shock-resistant (see Appendix C for the original Navy communication concerning these units). It will arm at a depth of 800 ft. and explode at

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<sup>1</sup>Frosch, Klerer, and Tyson, 1961, op. cit., p. 1805.

4,000 ft.

One of these units was detonated in the sound channel at a distance of 800 kilometers from Bermuda, and was clearly heard (20 db S/N) over the U.S.N. Underwater Sound Laboratory hydrophones located in the sound channel near the island. Thus the size of the explosive was proven to be satisfactory.

The fact that the Navy offered to supply these safe explosives at no expense to the project was a powerful incentive to their use. However, a pressure-detonated explosive poses several problems. First, in order that the bomb should go off at a particular time, it is necessary that the WHA-1-68 be protected from high pressure until that time. Therefore the bomb must be inside the float, and the timer must cause water to be admitted, thereby raising the pressure, at the correct time. Having the bomb inside, however, requires that the float be made of glass (rather than metal) so as not to attenuate the explosion. A spherical glass float would be a good choice anyway, but admitting water through the glass requires either expensive feedthrus and valves, or some method of breaking the sphere.

The cheapest and most readily available glass hemispheres are the ten-inch diameter variety made by Corning Glass Works (\$29 per hemisphere). A single quarter-inch hole drilled through the glass, however, costs about \$20 additional, and a high-pressure electrically actuated valve costs at least \$25. Under the severe cost restrictions of this project, the use of such a feedthru valve was not acceptable.

Therefore a method had to be found of breaking the sphere under pressure. An experiment conducted by Benthos Corp.<sup>2</sup> demonstrated that a #6 blasting cap

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<sup>2</sup>Private communication with S. Raymond, President, Benthos Corp.

would reliably puncture a glass sphere under pressure. The blasting cap, which costs only 25 cents, need only be glued to the inside of the sphere. This method has the advantage of extremely low cost and simplicity, and furthermore there is no difficulty due to corrosion of valve parts exposed to the sea.

Of course, a blasting cap poses a safety hazard of its own, in two ways. First, it could cause injury directly, should it explode accidentally while on deck or during handling or launching. Secondly, an accidental detonation of the blasting cap might trigger the main explosive, thereby causing much more serious injury or death. To help prevent accidental detonations, a magnetically operated glass reed switch was attached to the inside of the sphere and connected in series with the blasting cap. The magnet which operated the switch could be taped to the outside of the sphere, thereby assuring safety even after the timer had been set and the unit sealed.

At the author's request, the Bureau of Naval Weapons, Explosives Engineering Research Division, undertook a test to determine whether or not a #6 blasting cap could accidentally trigger the WHA-1-68. The result of the test was (again see Appendix C) that in the Navy's opinion, there was no danger.

In summary, the float consists of a glass sphere containing a pressure-actuated explosive, a blasting cap, and a preset timer. At the appointed hour, the blasting cap will be detonated by the timer, causing the sphere to leak or break. Exposed to ambient pressure, the explosive will arm, and after sinking to 4,000 feet, will explode.

On July 25, 1968, a test was conducted by the author off Bermuda to demonstrate that the above method of generating noise does in fact work (see Appendix B for details). The result was an unqualified success.

Lastly, it should be recognized that the least essential feature of the explosive float is the use of the blasting cap. Any other method of admitting water into the sphere would serve equally well, and if sufficient funds should become available, the author will substitute a more expensive but less dangerous device.



## B. Preset Timer

The preset timer must trigger the blasting cap at the desired time, which may be many days after deployment. At the end of this period its inaccuracy must be at most a few minutes since, as mentioned in Chapter IV, each float must be identifiable by the timing of its explosion. Calculating roughly, ten days is  $10^6$  seconds, and 100 seconds is an acceptable margin of error, so the required accuracy is about one second in  $10^4$ .

The author was unable, after considerable experimentation, to produce a simple electronic timer circuit with  $10^{-4}$  accuracy. Size, power drain, complexity, and cost all had to be minimized; for these reasons a mechanical clock triggering a preset counter was decided upon.

A transistorized clock movement (General Time Corp., model TR-3), modified by the addition of low viscosity oil and a high-gain transistor, was selected. Its cost including the modification was about \$9. Tests proved that its rate could be set to within one second in  $10^5$ , and varied less than one part in  $10^5$  per volt or per degree centigrade. It is specified to run for one year on a single "C" cell.

Once per hour the clock contacts close and trigger a low cost preset counter (HECON, model FE065.1, \$12). Circuitry had to be designed to avoid multiple triggering due to contact chatter, and to minimize the drain on the preset counter battery. See Figure 4 , page 30, for the schematic.

In addition it was considered necessary to have a back-up system, should the clock fail. A simple assured-destruct system, utilizing the controlled run-down of a small battery, sensed by an FET, was used. Again refer to Figure 4 . This small battery (TR 115R) is designed to run down after the preset time but before the main battery (RM 412) is exhausted.

For test purposes a flashbulb made a reasonable substitute for the blasting cap. The circuit worked well in laboratory tests. The average current drain on the first test unit was measured to be five micro-amperes; at that rate, the RM 412 battery (160 mah) should last 30,000 hours (more realistically 7,000 hours, which is shelf life).

The total cost of the entire preset timer unit was less than \$30, excluding the bomb itself.



## CHAPTER VI. DEVELOPMENT OF THE DEPTH TELEMETRY UNIT

### A. Preliminary Considerations

The first question was, what type of depth sensor should be used? Pressure transducers, although the most direct method, were rejected because of the high cost of accurate units, and the high cost of feedthrus. Acoustic methods, such as timing the bottom echo from a pinger, were rejected because of the uncertainty of receiving a suitable echo. A "sing-around" circuit was tried, consisting of a pinger whose rate was controlled by the acoustic travel time from the float to the surface and back; this was rejected because of cost and complexity.

A temperature sensor is the least accurate but easiest and cheapest depth measure. The average thermal gradient at a depth of 1,000 meters in the ocean near Bermuda is found to be  $1.5^{\circ}\text{C}$  per 100 meters.<sup>1</sup> Five meter depth accuracy therefore involves measuring temperature to within  $0.08^{\circ}\text{C}$ . Unfortunately the actual temperature field in the ocean varies with time, over long periods due to seasonal change, and over short periods due to turbulence and internal waves. The long period variations merely make it difficult to establish an absolute depth reference; that is, if only the local gradient at some depth were known, not the actual temperature, then it would still be possible to determine the relative depths of the floats.

The short-period variations are more difficult. Experiments indicate that there is significant energy in internal waves for periods of the order of one-half hour.<sup>2</sup> Thus, unless all the floats can transmit their temperature

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<sup>1</sup>F.C. Fuglister, op. cit., p. 37.

<sup>2</sup>B. Haurwitz, H. Stommel, and W.H. Munk, "On the Thermal Unrest in the Ocean", Rossby Memorial Volume, Rockefeller Inst. Press, New York, pp. 74-94, 1959.

information to the surface ship within a few minutes, it is necessary to pre-filter the temperature sensor. Acoustic transmission is not well suited for multiplexing, so the telemetry must be sequential; thus, allowing three minutes for each float, the total time required to complete the telemetry cycle is one hour. Clearly, each temperature sensor must have a  $1/e$  response time of at least two hours.

Having selected temperature as the measure of depth, the fundamental problem was to design a telemetry system as inexpensively as possible. Acoustic transmission requires fairly high power levels (especially since the floats and the surface ship may become separated by several miles), so that low duty cycle pulsed transmission is necessary to conserve power.

The most effective pulsed transmission would be the master-slave type. This would require a series of master pulses at a very accurate rate, each followed by a slave pulse whose separation from the master would be determined by the temperature. If a recording instrument with a repetitive sweep (such as a Precision Graphic Recorder) is used as a receiver, the human eye can pick out the slave pulses even for a S/N ratio lower than 0 db. Unfortunately, an accurate master pulse generator was found to cost too much.

Nearly as effective is the simple rate-controlled oscillator, which emits pulses whose repetition rate is related to the temperature. The received signal will be periodic (or slowly varying) so that a correlator is the optimum detector. It was found that a cheap but accurate temperature-controlled oscillator is feasible, and of course the human brain is an excellent correlator for acoustic signals.

It would be well at this point to discuss more fully the method of receiving the signal and calculating the pulse repetition rate. First the acoustic signal must be picked up on a hydrophone, amplified, and filtered.

Then the signal can be fed into any or all of three types of detector, as follows: (1) If the S/N ratio is 20 db or more, a simple threshold detector (no memory) may be used, coupled with an electronic counter set to read "period". But if S/N is less than 20 db, a threshold effect will occur, causing many false triggerings; (2) A pair of headphones will enable a person to monitor the signal by ear; the brain can reliably detect a periodic signal as low as 10 db S/N. Measuring the period can be done by counting with a stopwatch; (3) A graphic recorder will enable the eye to pick out a periodic signal lower than 0 db, but this requires (a) a graphic recorder (PGR) with a continuously adjustable sweep repetition rate, and (b) a rough knowledge of the period that is to be observed. The audio method is of course the cheapest by far.

It should be understood that the depth telemetry need not continue for the entire time that the floats are in the water. We desire to determine their depths soon after deployment, say within twenty-four hours. Therefore the telemetry section has been designed to transmit for only two days before the batteries give out.

## B. Design of the Pulse Generator

Functionally the transmitting system is composed of three separate parts: a temperature-controlled pulse generator; an acoustic power driver and transducer; and a timer for sequencing. This section deals with the former.

The pulse generator must produce very short pulses whose rate is a continuous function of temperature. The rate must range from 3 pulses per second to 1 pulse every 2 seconds, approximately; this range allows counting by ear. The temperature range must be from  $5.5^{\circ}\text{C}$  to  $8.5^{\circ}\text{C}$ , which represents the depth range 900-1,100 meters at a location south of Bermuda. Furthermore the drift and jitter at a constant temperature must be negligible (i.e., no more than a few parts in  $10^3$ ). For example, if we wish to resolve 5 meters in depth (out of 200 meters full scale), at about a one-second rate we must be able to resolve 20 ms in period.

The chosen design involves an Integrator (ramp-generator) whose output voltage increases at a rate inversely proportional to the resistance of a thermistor. When the ramp has risen to a certain voltage, a Voltage-Triggered Pulse Generator (VTPG) generates a 2 ms pulse which causes the integrator to be discharged. Figure 5 , page 37, is a functional block diagram of the circuit.

The integrator itself is an operational amplifier (Analog Devices, Inc., model 105 A) with a mylar capacitor in the feedback loop. Its input is the difference of two currents, one of which is controlled by the thermistor (this allows the sensitivity to be varied). See Figure 6 , page 38, for the schematic.

The discharge circuit is an SCR (Texas Instruments TIC 44) across the capacitor. An SCR, however, will never discharge a capacitor completely, and the cutoff point is temperature-sensitive; therefore an additional means had

FIGURE 5

FUNCTIONAL BLOCK DIAGRAM OF THE TEMPERATURE-CONTROLLED  
PULSE GENERATOR

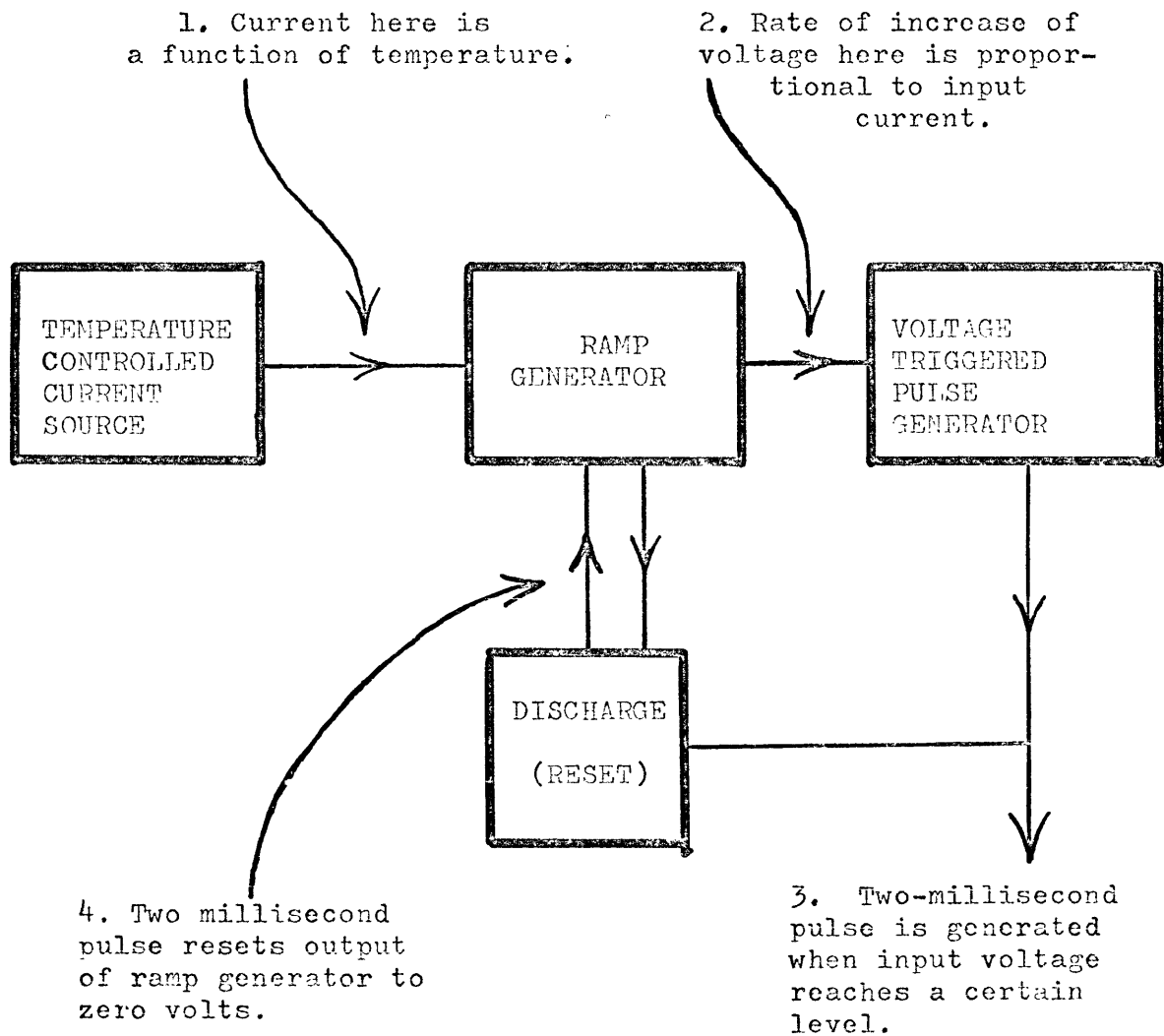
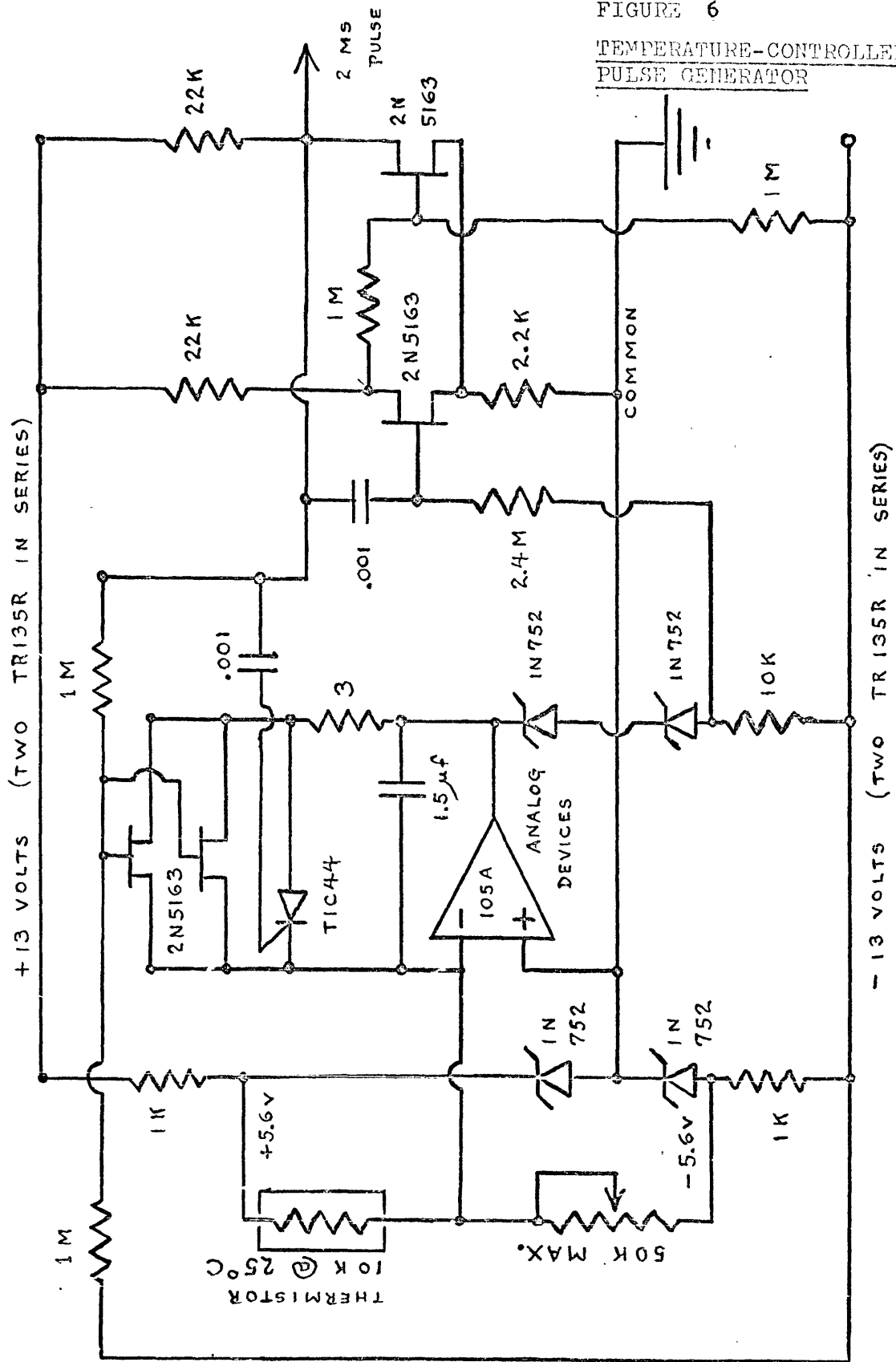


FIGURE 6

TEMPERATURE-CONTROLLED  
PULSE GENERATOR



to be found to complete the discharge. The device selected is a JFET (Fairchild 2N5163) which according to specification has a saturated drain-to-source resistance of at most 500 ohms, and whose drain current curves go through the origin. Two such devices in parallel with the SCR are found to discharge the capacitor to zero within one millisecond.

The Voltage-Triggered Pulse Generator also makes use of the 2N5163, mainly because of its low cost (35¢) and lack of loading problems. The design is basically a monostable with the discharge resistor connected, through a level-shifter (zener), to the ramp generator. See Figure 6 for detail.

Referring to Figure 6, we see that possible sources of significant temperature drift are: (1) the operational amplifier, (2) the input reference zeners, (3) the capacitor, (4) the discharge circuit, and (5) the Voltage-Triggered Pulse Generator. The components were selected so that the first three factors became negligible (for example, the zener diodes used were IN 752's which have the lowest temperature coefficient).

A critical factor was found to be the current injected into the gate of the SCR (and hence into the inverting terminal of the operational amplifier) during the 2 ms discharge pulse. Two hundred microamperes minimum is necessary to fire the SCR, whereas the temperature input current into the inverting terminal is normally ten microamperes. The effect of this large unbalanced current appears as a variable negative voltage across the 1.5 microfarad capacitor, which of course eliminates the virtues of a complete discharge. Therefore it was important to allow as little current as possible into the gate of the SCR, hence the .001 microfarad capacitor, as shown in Figure 6.

Furthermore the level-shifting zener diodes on the input of the VTPG proved to be critical. To achieve the desired stability it was necessary to use two or three of the 5.6 volt IN 752's in series, rather than a single 13 volt IN 964.

The thermistor used was selected for its low cost (80¢). It is specified to be 10 K ohms at 25°C,  $\pm 10\%$ . In order to achieve the long overall time constant necessary, the thermistor is first potted, then attached to the circuit board away from the float wall.

The remainder of this section will deal with the tests that were conducted upon the first few completed oscillator units.

The reader will no doubt have noticed that each temperature telemetry unit must be calibrated to better than 1% accuracy. It proved impractical to calibrate the unit as a whole to the required accuracy, and therefore it was necessary to first calibrate the resistance of each thermistor as a function of temperature, and then calibrate the period of each pulse generator as a function of resistance. Tests on the first unit constructed showed that the temperature drift with a fixed resistor in place of the thermistor was 0.06%/°C, which is negligible. Figure 7, page 41, is a plot of output period versus resistance for the same unit. Figure 8, page 42, which is a plot of output period versus temperature, is a combination of Figure 7 and a plot of resistance versus temperature for the thermistor.

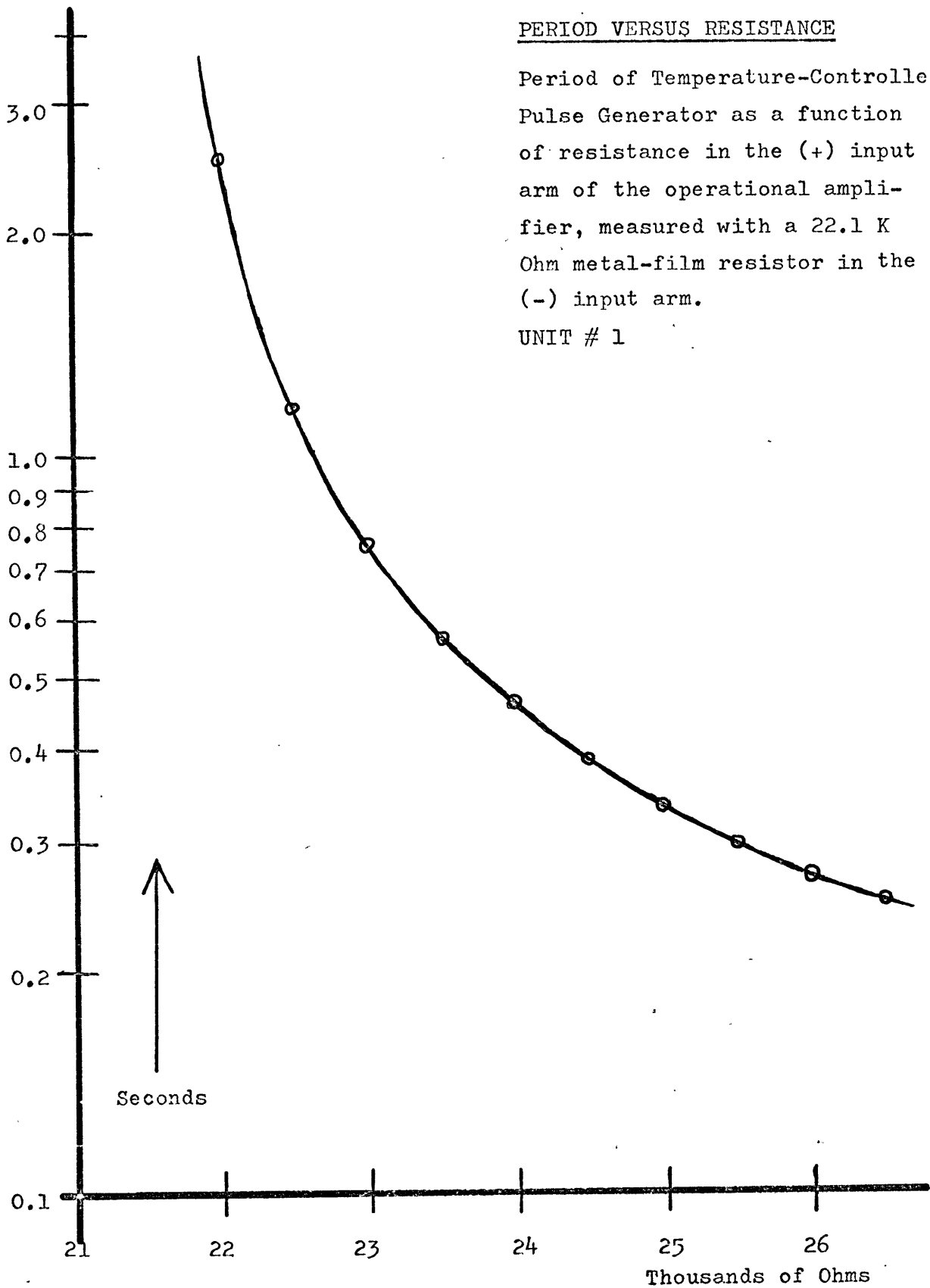


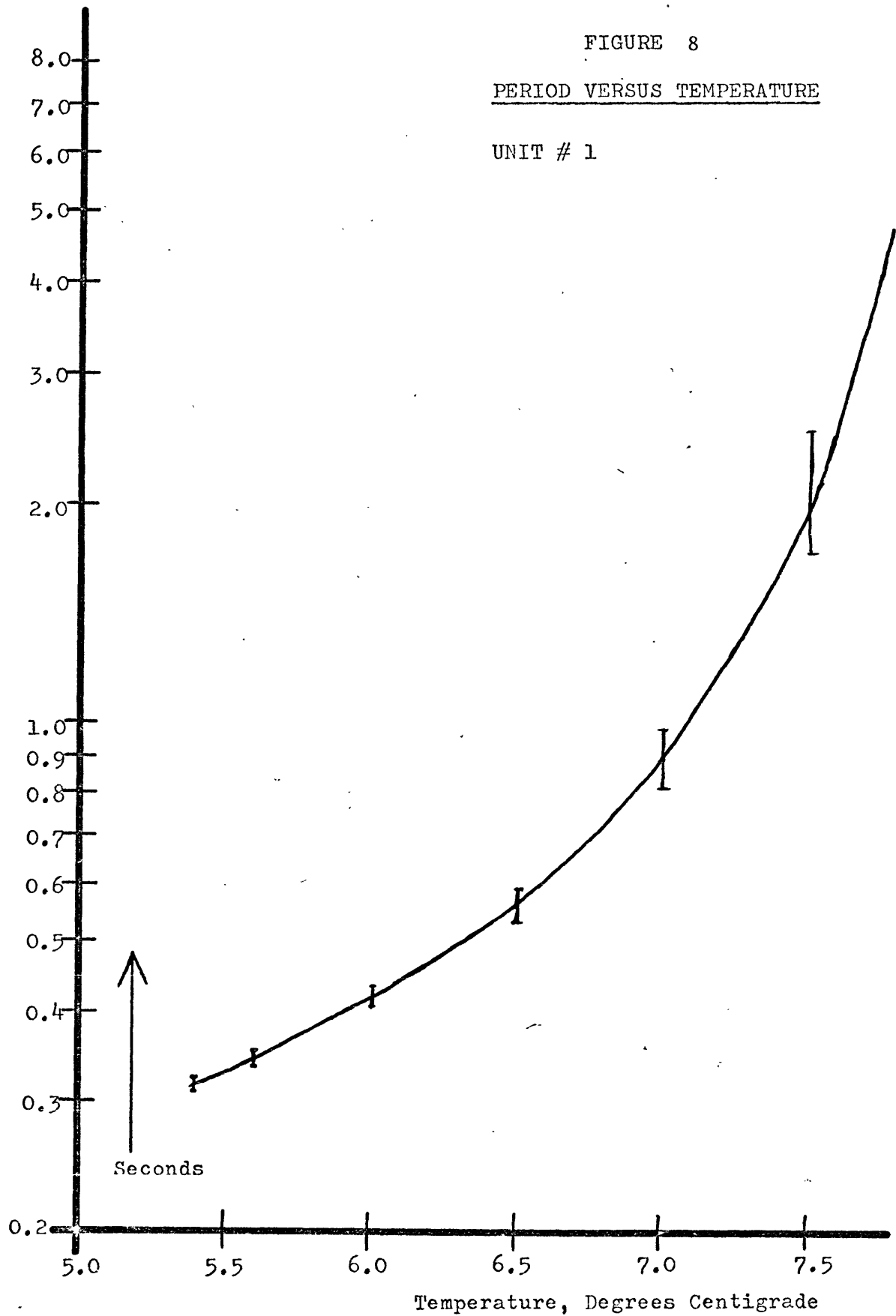
FIGURE 7

PERIOD VERSUS RESISTANCE

Period of Temperature-Controlled Pulse Generator as a function of resistance in the (+) input arm of the operational amplifier, measured with a 22.1 K Ohm metal-film resistor in the (-) input arm.

UNIT # 1





### C. Design of the Acoustic Power Circuitry

The 2 millisecond output pulse from the VTPG is used to trigger an acoustic power transducer circuit. Unfortunately, transducers are expensive and so are transformers to drive them, as well as feedthrus to connect them. Thus it was a piece of financial good fortune that twenty transducers, of a type that does not require feedthrus, became available at no cost to the project. These transducers consist of a ten inch ring of barium titanate, silvered on the flat parallel faces. The ring is installed between the two glass hemispheres, and when excited causes the whole sphere to radiate sound. Unfortunately, the transducers had proven in prior experiments to be rather inefficient and difficult to drive (this was in fact why they were available). The cost advantage was irresistible, however, and so a simple and inexpensive driver circuit had to be devised.

The circuit which evolved is admittedly the least sophisticated one in this project. It is a shock excitation circuit utilizing capacitative discharge through the primary of a loosely-coupled step-up transformer.

The transducer, being a high-impedance crystal device, requires very high voltages to drive. Prior tests revealed that when installed between two ten-inch hemispheres it has a resonance at 6.18 KHZ, at which point its series impedance is 460 ohms and 0.012 microfarad. Clearly, in order to dissipate 100 watts in this device, voltages of the order of 2,000 volts are necessary.

A typical driver circuit for this transducer would consist of a multi-vibrator driving a push-pull output circuit. A step-up transformer and a loading coil, both capable of taking high voltages and high power levels, would be necessary. A price investigation showed that such a circuit could not be built for less than about fifty dollars. Furthermore transformers

and loading coils capable of high voltages tend to be heavy, and weight was a problem since the total payload had to be less than twelve pounds (the payload of a ten-inch sphere). For these reasons the typical driver circuit was unacceptable.

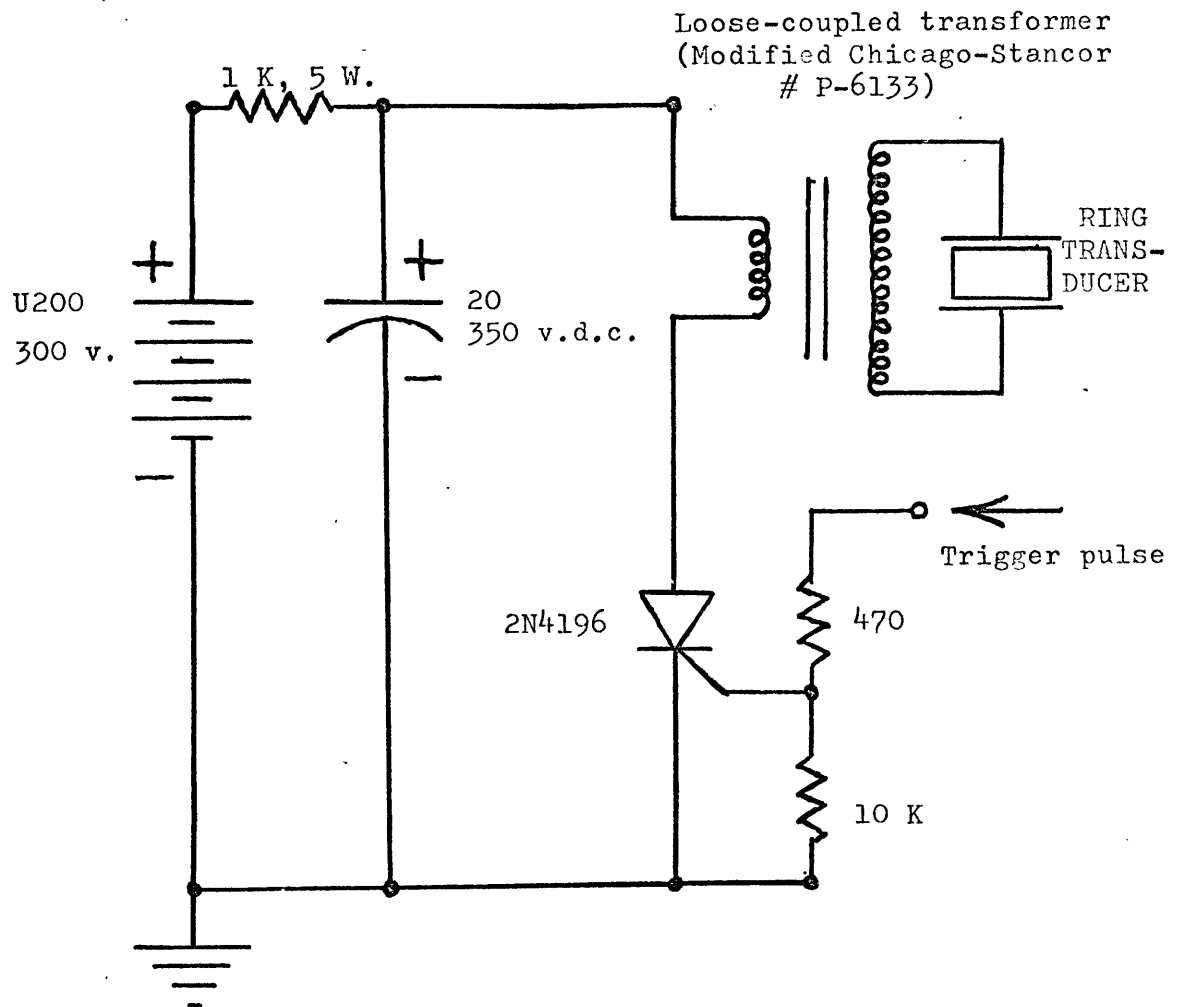
A loosely-coupled transformer (one whose core has an air gap) can double as a loading coil, since each winding exhibits a constant inductance. This fact suggested that the solution might consist of an inexpensive transformer modified so as to be loosely coupled. A suitable unit was found to be a Chicago-Stancor filament transformer (#P-6133, \$4.84) which is rated at 7,500 volts RMS. The modification consisted of disassembling the laminated iron core, then reinstalling part of the iron in such a way that a large air gap was left. The transformer had to be operated in reverse (i.e., the old secondary became the new primary, and vice versa), and the new secondary inductance had to be 59 millihenries (which is the correct inductance to resonate with the transducer at 6.18 KHZ). The secondary inductance was adjusted by varying the number of iron laminates in the new core.

Obviously the idea of a loosely-coupled transformer is not ideal. Its use entails the sacrifice of efficiency for cost and weight. Part of the weight and cost advantage is lost, however, because the decreased efficiency requires heavier and more expensive batteries in the power supply. Fortunately, batteries proved to be less heavy and expensive than transformers and coils, so a net gain was achieved by this trade-off.

The primary side of the circuit consists of merely a capacitor discharging through an SCR into the primary winding (shock excitation). It was found to be necessary to use a high-voltage battery to achieve the desired acoustic levels. Figure 9 , page 45, is the schematic of the entire circuit.

FIGURE 9

ACOUSTIC POWER OUTPUT SCHEMATIC



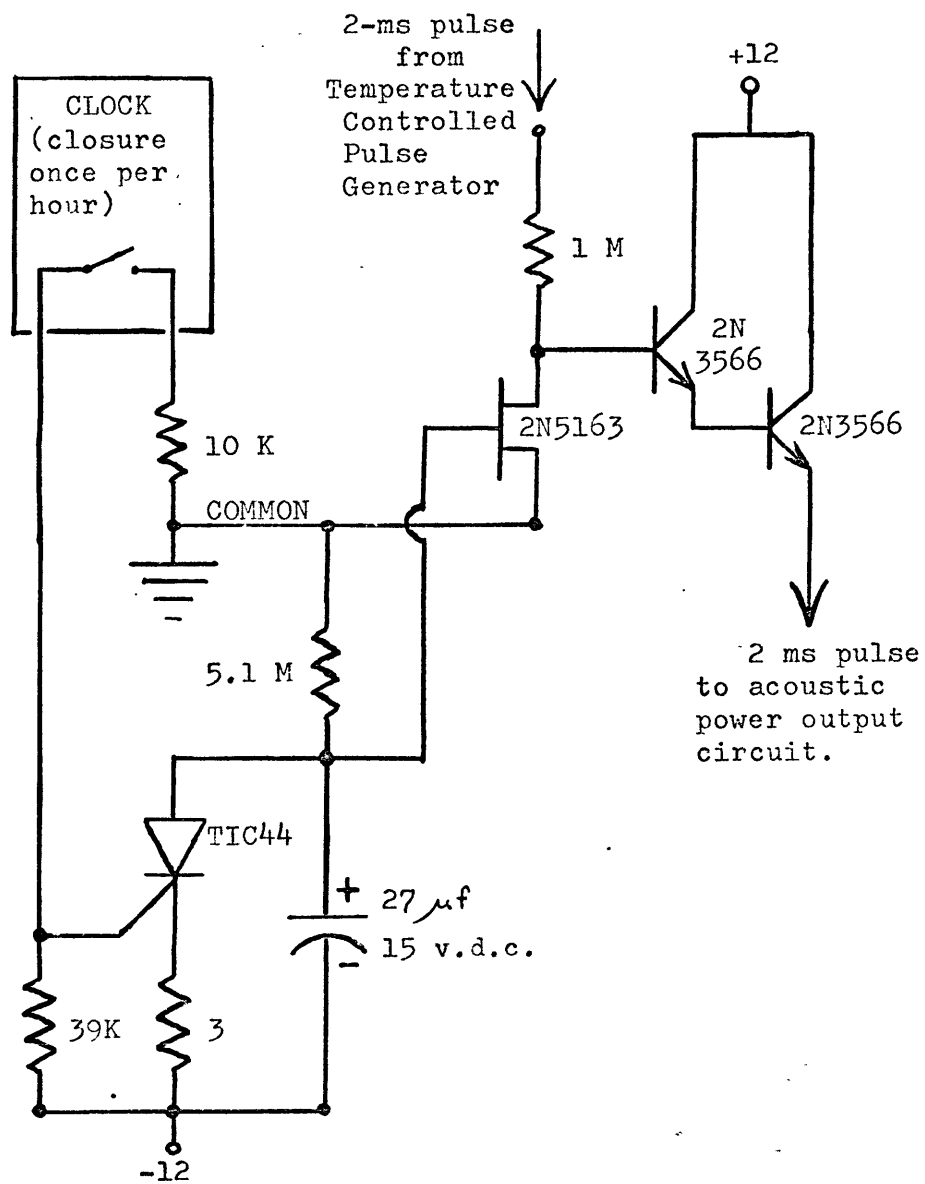
A word is in order here about the acoustic power level. Through experience and private conversations, the author had concluded that an acoustic power level of 75 db re 1 microbar at a range of 1 meter from the float should be audible over a distance of three miles, if the sea is quiet and the transmission paths are favorable. However, one cannot depend on having favorable conditions, and thus it was necessary to design for the maximum possible output power under the restrictions of cost and weight, rather than design for a particular power level.

The design shown in Figure 9 was tested in water, and it proved capable of putting out "ringing" pulses of nearly 80 db. Further significant improvement would require a complete re-design and much heavier components; for instance, the instantaneous voltage level at the secondary of the transformer is as high as five thousand volts in the design shown, but to increase the output by 10 db would require fifteen thousand volts and consequently a prohibitively large and expensive transformer.

In summary, the design of the acoustic power unit is crude but cheap; the author knew of no way to improve it significantly under the rigid cost requirement. The total cost of the power unit came out to be under \$20, including the battery but not the transducer.

FIGURE 10

SEQUENCING TIMER SCHEMATIC



#### D. Design of the Sequencing Timer

As mentioned in Chapter IV , it is necessary that the telemetry be sequential; that is, that the floats transmit their depth information one at a time. The floats have no communication with each other, and therefore the sequencing must be done from the main timers (which are used for timing the explosions). The entire telemetry of all twenty floats must be completed within one hour, that being the basic time period of the clocks in the timer section. Each float must therefore transmit for three minutes out of every hour.

The timer clocks, which were described in Chapter V, were provided with an additional contact whose closure time with respect to the hourly contact could be varied. By this means each float could be made to transmit for a different three minutes out of every hour.

In order to avoid contact chatter problems, it was necessary to use an SCR and capacitative discharge circuit (triggered by the contact closure) to provide the three-minute timing. The sequencing schematic is shown in Figure 10, page 47.



## CHAPTER VII. CONCLUSION

This project has conveniently divided itself into two separate parts. First there was the conception of the basic idea, involving the design of an oceanographic experiment, and secondly there was the design and construction of a system with which to perform the experiment. This distinction must be considered in any analysis of the project.

### A. General Advantages

Insofar as the oceanographic aspect is concerned, this project represents, not a new method of measuring currents, but a significant refinement of an old method. It makes use of the properties of the sound channel in a way never before done, and it offers the promise of results of a kind not previously achieved. It extends the usefulness of Swallow floats to much greater ranges and observation times. As an additional benefit, only a relatively small amount of ship time is necessary.

The system itself has several noteworthy features. First is the relatively low cost in view of the performance; this will be discussed in more detail further on. The use of pressure-detonated explosives and the method of breaking the sphere were innovative solutions to the problem of creating sound. Furthermore, the system is designed so that even if the most complex part of the circuit should fail (the depth-telemetering section), all would not be lost, because the simpler explosive section is completely independent.

## B. General Disadvantages

Certain disadvantages of the system are ~~more~~ evident. The one-shot nature of the floats makes continuous tracking impossible, and a great deal of detailed data is lost thereby. This lack of continuous data is partially offset by the strategem of breaking up the experiment into three successive smaller experiments, but in the trade-off a certain amount of statistical reliability is sacrificed. Thus in general the system is useful only for making average measurements, rather than detailed studies of the structure of the currents.

Furthermore, the system as described can only be used to measure currents shallower than the axis of the sound channel; this is due to the arming sequence requirement of the pressure-detonated bomb. Measurement of deeper currents would require extensive modifications of the floats.

The system is also somewhat cumbersome to deploy, involving the careful ballasting of many Swallow floats, but of course most other techniques of current measurement are even more cumbersome.

### C. Critical Analysis of Circuitry

The timer circuit is sufficient unto the purpose. It is simple and relatively foolproof, although its design involves nothing new or noteworthy. Its cost, being under \$30, is quite reasonable for a preset timer with  $10^{-4}$  accuracy. The low cost, plus its ability to operate for long periods at very low power levels, recommends its use in future oceanographic equipment.

The temperature-controlled pulse generator is the most sophisticated of the circuits, and it involved the greatest amount of effort. It is noteworthy for its use of FET's, for instance in their innovative application in the discharge circuit. The use of FET's also made possible the simplicity of the Voltage-Triggered Pulse Generator section. The overall cost of the temperature-controlled oscillator was less than \$50, which seems reasonable considering its stability and sensitivity. In retrospect, certain improvements come to mind, such as the use of an integrated-circuit operational amplifier, or, better still, a low-power operational amplifier, and the use of a polycarbonate capacitor in the feedback loop instead of mylar (polycarbonate has a lower temperature coefficient at near-zero temperatures).

The acoustic power circuitry has little to recommend it except its cost, which is less than \$20. The cost of the transducer itself is of course not included because that item was available without cost to the project; had equivalent transducers been purchased, they would have cost about \$75 each.

The sequencing timer is worthy of note because of its use of an FET as a high-impedance sensing device. The circuit combines the functions of a three-minute pulse generator and positive-closure switch in a very simple package. Its cost is only about \$5.00.

Under the heading of general considerations there are a number of costs

which cannot be attributed to the individual circuits. The spheres, the stainless steel straps to hold them together, and the rubber bands to seal them cost about \$60 altogether. The printed circuit board upon which the circuits were assembled cost about \$15. An additional expense which was not charged to the project was the pressure-detonated explosives. The U.S. Navy kindly provided these without cost, and without any information about their true cost to the government.

The total cost for all parts for each float came to approximately \$180. This price is higher than the \$125 price called for in the original proposal, but nevertheless it is quite low. The original estimate failed to account for the expense of certain critical components in the temperature-controlled pulse generator, for the high cost of batteries, and for a major price increase in the cost of glass hemispheres. Despite the increased cost, it would seem that the development has been a success from the point of view of producing a device which serves the purpose at a reasonable cost.

D. Comments on Test Results

All the circuits described in this report were tested in the laboratory, separately at first, and then after all the components had been assembled in close proximity on the circuit board. The tests were carried out at near-zero temperatures to ensure that environmental conditions were faithfully duplicated. In all these tests, the results were uniformly satisfactory after a few "bugs" had been removed.

The first completed and fully tested unit was deployed off Bermuda in a full scale dress rehearsal, and was lost (see Appendix B). Neither the telemetry nor the explosion was heard, which perhaps implies that something catastrophic occurred, rather than just failure of a circuit. For instance, the ballasting operation could have been wrong. The failure of this test does not necessarily imply that the circuitry was inadequate.

At the same time that the above test was done, a tethered test was performed (again see Appendix B) solely to check the operation of the explosive mechanism, and this test was successful. Due to lack of time, no further tests could be performed. One must conclude that the testing program was somewhat incomplete, since the system has not yet completed a successful test run. However, there is little doubt that once deployed, the system will operate properly. In this sense, therefore, the laboratory tests were adequate.

E. Relation of Result to Proposal

It was naturally disappointing that the oceanographic phase of the project could not be included in this thesis, as proposed. This situation came about, not as a result of any gross misjudgment, but rather because of the nature of the project. One must realize that the project proposal submitted to ONR (the source of funds) necessarily included both phases, and all the work had to be planned on that basis. Thus there was some possibility that, if the work went extremely well, both phases could be included in the thesis. Realistically, it was recognized that this might not be possible. Thus the absence of the oceanographic phase here is hardly to be regretted. The work is continuing.

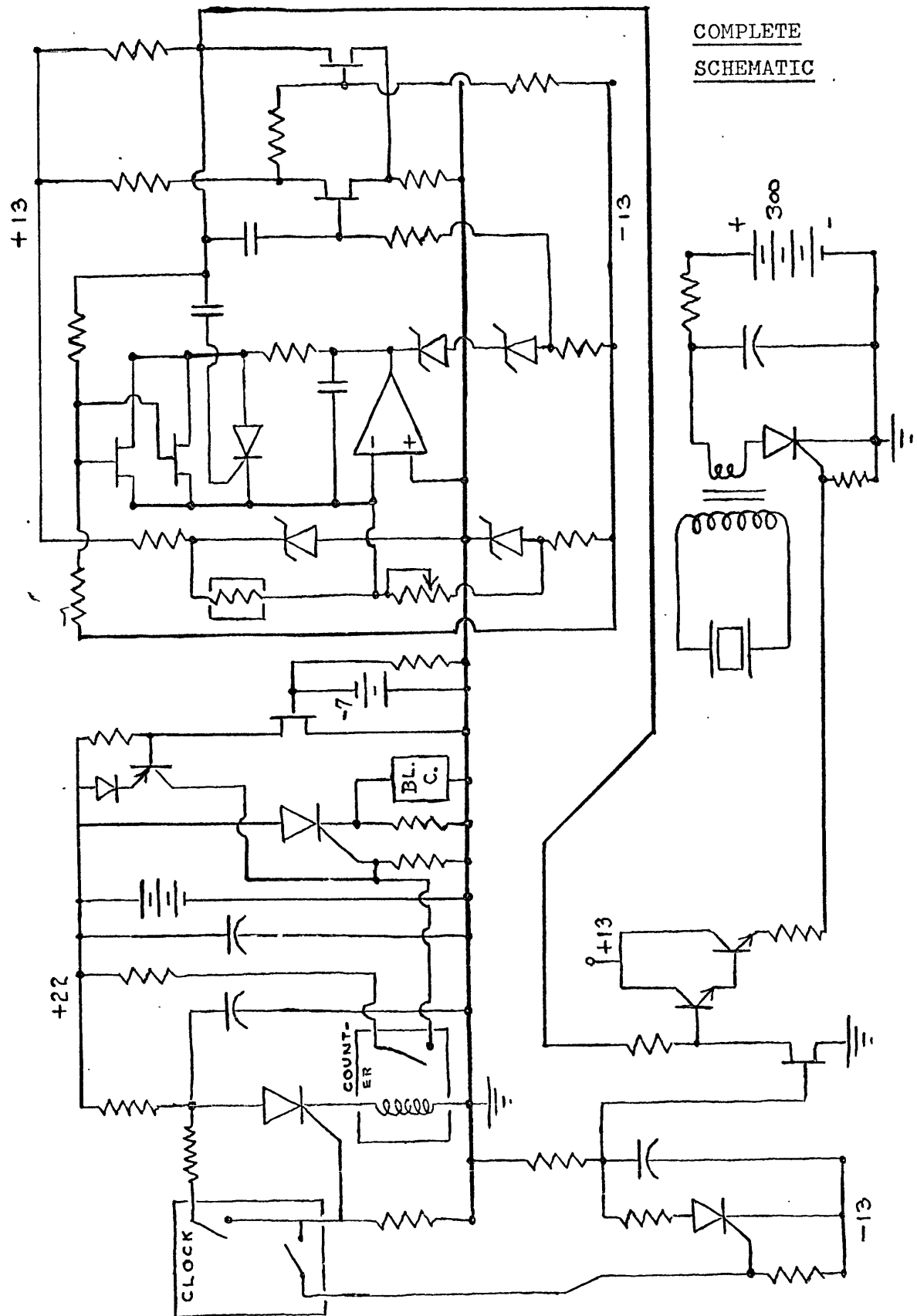
## APPENDIX A

### Complete Schematic, Photographs, and Cost Lists

Figure 11, page 56, is the complete schematic of the float electronics.

On page 57 is a complete cost list of all components used. The prices given are the unit prices for quantities of twenty, which was how the components were purchased.

FIGURE 11





Cost List

	#	Total \$
1. Clock, General Time Co., Model TR3	1	3.95
2. Modification to TR3	1	4.95
3. Preset Counter, Hecon Model FE065.1	1	12.00
4. Capacitor, 500 $\mu$ f, Sprague TVA 1209	2	2.76
5. SCR TIC 44	4	2.24
6. Magnetic Switch, Hamlin, type DRG-DTH	1	2.50
7. Diode, IN461	1	0.53
8. Transistor, Fairchild 2N3638A	1	0.35
9. Transistor, Fairchild 2N3566	2	0.70
10. JFET, Fairchild 2N5163	6	2.10
11. Thermistor, Fenwal #	1	0.80
12. Zener diodes, IN752	5	10.00
13. Potentiometer, Bourns #3068 P-503	1	1.71
14. Operational Amplifier, A.D. 105A	1	15.00
15. Capacitor, 1.5 $\mu$ f Mylar (TRW)	1	2.60
16. Capacitor, 27 $\mu$ f Tantalum (Sprague)	1	2.20
17. Capacitor, 20 $\mu$ f 350 VDC (Sprague)	1	1.77
18. SCR, Motorola 2N4196	1	2.94
19. Filament Transformer, C.S. #P-6133	1	4.84
20. Small capacitors	2	1.00
21. Resistors, 1/4 w	23	2.99
22. Battery, 1.5 r., Eveready # E93	1	0.50
23. Battery, 22.5 r., Mallory # RM412	1	2.76
24. Battery, 6.75 r., Mallory # TR115R	1	2.06
25. Battery, 6.75 r., Mallory # TR135R	4	8.00
26. Battery, 300 r., Burgess # U200	1	8.37
27. Battery Clips	6	2.40
28. Circuit board, HADCO	1	14.50
29. Glass hemispheres, Corning Glass Works	2	58.00
30. Stainless steel straps, Breeze Co.	1	0.65
31. Rubber Band, 2" wide, Plymouth Co.	1	0.30

Each Float, Total \$175.45

In addition, various miscellaneous items such as wire, solder, and grease raise the total to perhaps \$180 at most. This list does not take any labor costs into account, nor any ship time.

## APPENDIX B

### Discussion of the Bermuda Tests

On July 25, 1968, the author conducted two tests concerning the operation of the system in deep water off Bermuda. The first test was a tethered trial of the explosive mechanism, and the second test was a complete deployment of a finished float.

For the first test, a ten-inch glass sphere, equipped with a blasting cap glued to the inside, an inexpensive timer, and the pressure-detonated explosive, was attached to the end of a cable and lowered to 1000 meters. Both the blasting cap and the much louder high explosive were clearly heard over a hydrophone on the ship. This test proved that a #6 blasting cap will puncture a glass sphere under pressure, and that the explosive will arm and fire properly.

For the second test a completed unit, which had been previously tested in the laboratory, was ballasted according to the established procedures, and carefully deployed. The timer was set for 10 hours to allow the unit plenty of time to come to equilibrium. The pinger was not observed to function on deck; however, as examination of the telemetry schematic will show, this is a normal condition, because the telemetry does not function at high temperatures. After deployment, the most attentive listening failed to discern either the telemetry or the explosion.

The reasons for this failure are hard to find. It is possible that the temperature telemetry was acoustically obscured, but it is highly unlikely that the explosion would not have been heard. One must conclude that both circuits failed simultaneously, or else that the float sank to a vastly incorrect depth.

Clearly the second test should have been done differently. Too many factors could have accounted for the failure, and there is no way of knowing which was responsible. A tethered test, with the float suspended from a cable, might have been better, because in such a test there could have been no doubt about either the depth of the float or the audibility of the signals.

APPENDIX C

Communication from U.S. Navy regarding WHA-1-68

On the following pages are the text and photographs which were received from the Bureau of Naval Weapons, Explosive Engineering Research Division, Yorktown, Virginia, concerning the design and safety tests upon the pressure-detonated explosive.

RESULTS OF A SAFETY TEST  
CONDUCTED FOR  
SPECIAL SOUND SIGNAL, WHA 1-68

I. GENERAL

The Massachusetts Institute of Technology has requested that the Explosives Engineering Research Division of the Naval Weapons Station, Yorktown, design and fabricate 30 special underwater sound signals (hereby designated WHA 1-68). Since time was a factor in this request, it was decided to modify a Mk 38 Mod 0 Arming Mechanism (A&F) for utilization in the special signals.

The modification to the Mk 38 A&F consists of machining away a major portion of the brass body and nose cap for weight reduction. Also, the Tetryl lead was removed and a pickup cup designed for the EX 59 Mod 5 Sound Signal was installed in its place. A photograph of the modified WHA 1-68 Signal mounted on an aluminum plate is shown in Figure 1.

The main explosive charge is 0.45 pound of flexible explosive per MIL-E-46676A encapsulated in a clear, flexible, epoxy resin. This particular explosive (DuPont Detasheet "C") has a density of 1.48 gms/cc, a detonation velocity of 7000 meters/sec and the explosive ingredients are PETN (63%), nitrocellulose (8%), and the remainder is binder and dye.

II. APPLICATION OF SIGNALS

These WHA 1-68 Signals will be mounted on a 1/16-inch thick aluminum plate and installed in one-half of a 9-1/4 inch O.D. glass sphere. The other half of the glass sphere will contain a detonator and other associated equipment. The completed sphere will be deployed in an ocean environment.

III. PURPOSE OF TEST

The purpose of the test was to determine if accidental, or purposeful, firing of the electric detonator mounted in one-half of the glass sphere would cause the WHA 1-68 Signal mounted in the other half, to burn, detonate, arm, or suffer damage that would prevent functioning of the signal.

IV. DESCRIPTION OF TEST

The completed device employs a No. 6 electric detonator to rupture the sphere and permit outside water pressure to actuate the A&F in the signal. Since this particular detonator was not immediately available, it was decided to use an engineer's special electric detonator. This, of course, subjects the signal to a much more severe test since the engineer's special detonator contains a base charge of 13.5 grains of PETN whereas the No. 6 detonator contains a base charge of only 4.9 grains of PETN.

Enclosure (1)

The engineer's special detonator was placed in one-half of the sphere with the output end against the inner diameter at a point halfway around the sphere from the joint. The detonator was held in place with a conical shaped mound of RTV silicone rubber. The WHA 1-68 Signal was fastened to a 1/16-inch thick aluminum plate with two screw-type stainless steel hose clamps and the safety pin was removed from the signal. The signal-plate assembly was placed in the other half of the sphere with the aluminum plate interposed between the detonator and the signal. The completed unit, ready for firing is shown in Figure 2. Note that the hemispheres are held together by several turns of black electrical tape.

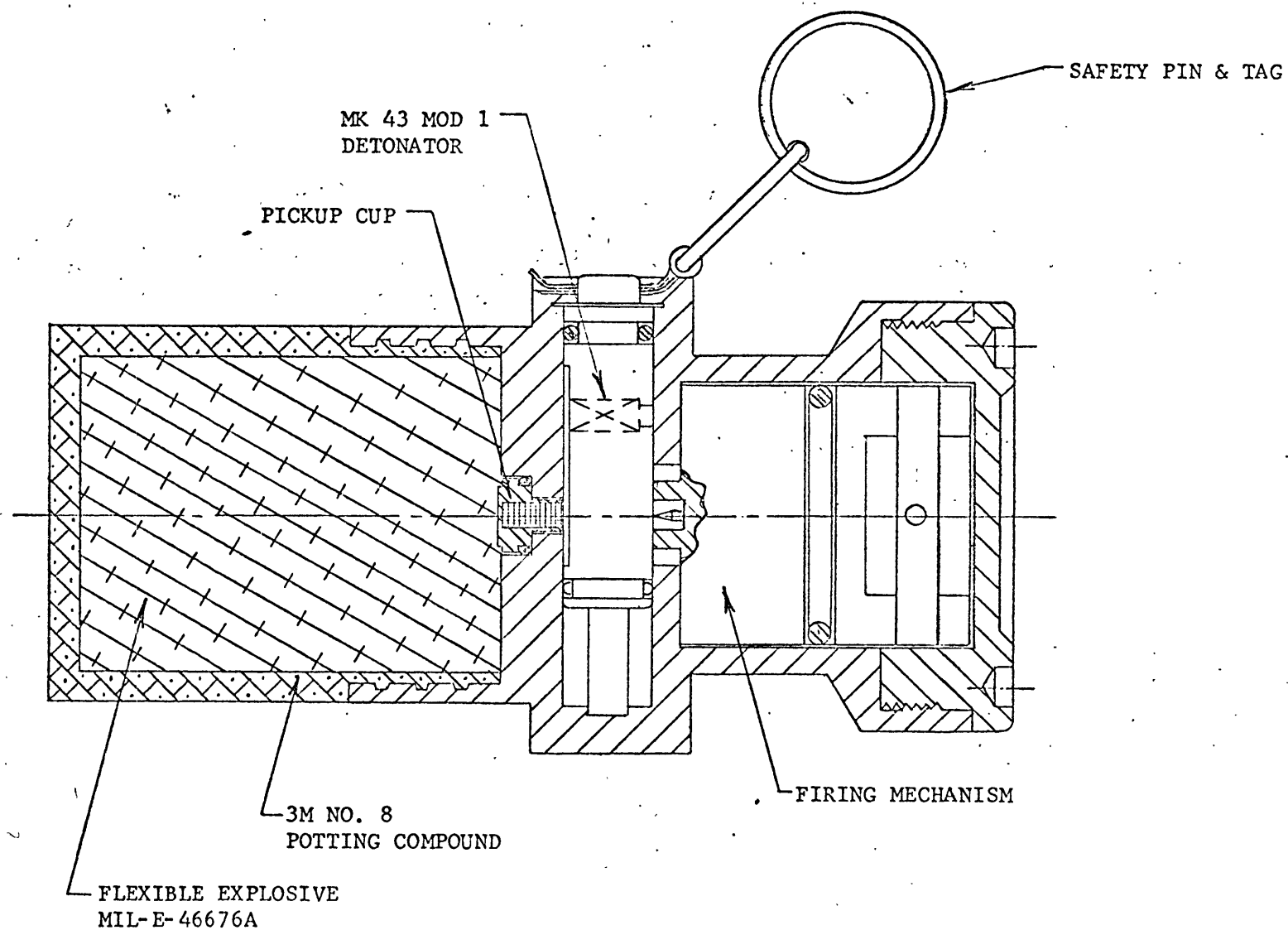
The detonator was fired and the recovered parts were examined. Both halves of the sphere were completely destroyed and small fragments of glass about one-half inch in diameter were found up to 25 feet away. The aluminum plate was essentially folded around the signal.

Figure 3 shows the signal and the remains of the sphere immediately after firing. Figure 4 shows the signal and the underside of the aluminum plate. The RTV silicone rubber used to secure the detonator to one-half of the sphere was blown through the holes in the aluminum shield plate and is shown sticking to the signal in Figure 4. After the test, the signal was disassembled and examined. None of the internal operating parts were damaged in any way and the signal should function as intended. Neither the explosive charge nor the epoxy surrounding the charge was damaged. The blast from the detonator did not cause the signal to arm. None of the parts of the arming or the firing mechanism had been displaced by the blast from the detonator.

## V. CONCLUSIONS

Even though only one test was conducted, it is concluded that a No. 6 electric detonator mounted and fired in one-half of a 9-1/4 inch glass sphere will not cause the signal, mounted in the other half of the glass sphere and shielded as herein described, to burn or detonate. The damage resulting from firing a No. 6 electric detonator would be considerably less than that caused by firing the engineer's special detonator used in this test. It should be pointed out that the primary hazard resulting from the firing of the detonator in this device would be from flying fragments of glass. Functioning of the signal should not be affected by the blast from firing the detonator.

The explosive used in this signal requires considerable shock to initiate it. In general, a No. 6 or larger electric detonator or equivalent must be in intimate contact with the explosive to detonate it. Any gap between the detonator and the explosive reduces the possibility of detonation.



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SPECIAL SOUND SIGNAL, WHA 1-68

Explosives Engineering Research Division  
 NWS Yorktown

SKETCH  
 JCW 4/4/68

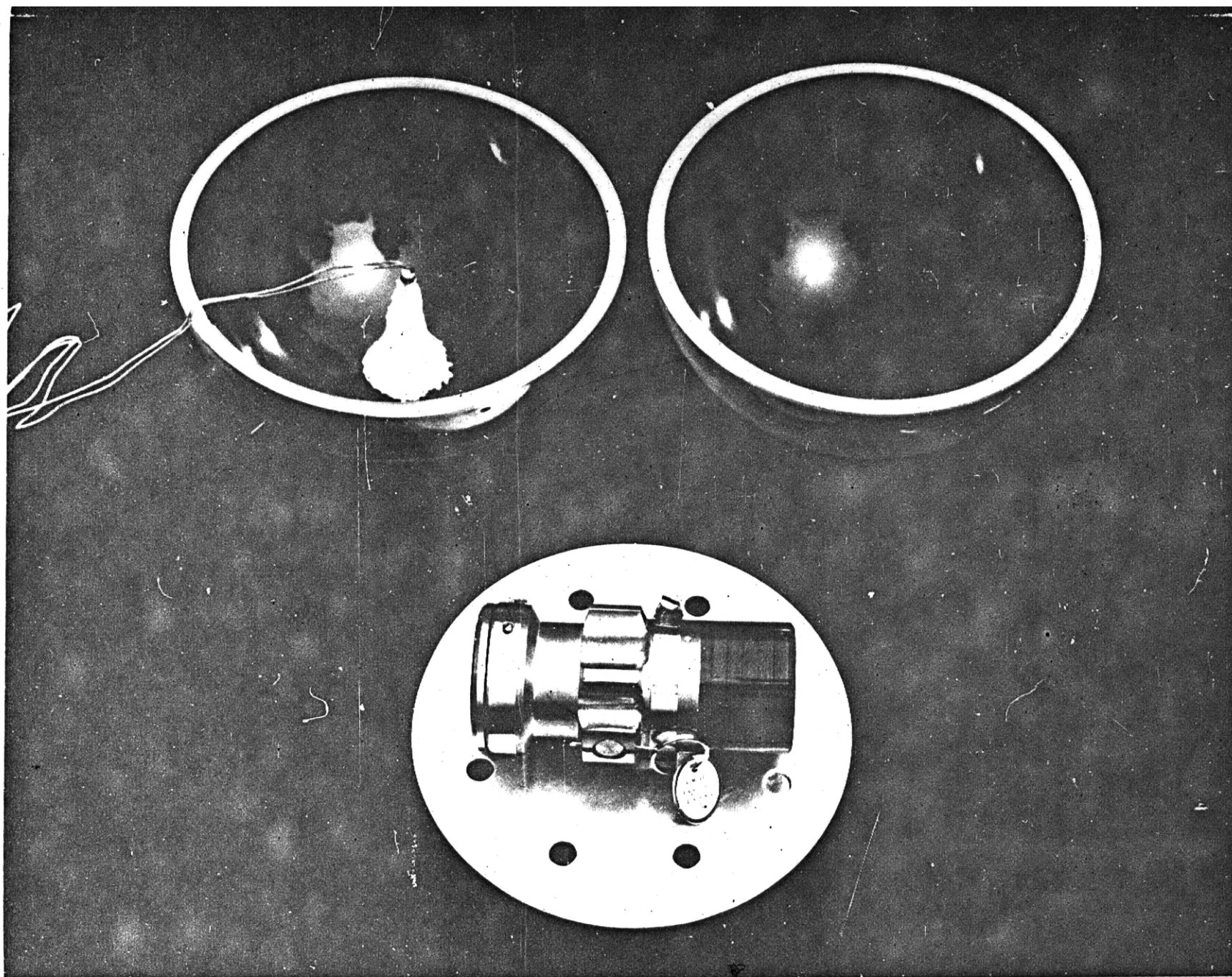


FIGURE 1





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FIGURE 3

BIBLIOGRAPHY

1. Bryan, G.M., Truchan, M., and Ewing, J.  
"Long Range SOFAR Studies in the South Atlantic Ocean", JASA, Vol. 35, #3, pp. 273 - 278, 1963.
2. Crease, J.  
"Velocity Measurements in the Deep Water of the Western North Atlantic", JGR, Vol. 67, #8, pp. 3173 - 3176, 1962.
3. Defant, Albert  
Physical Oceanography, Vol. 1, New York, Pergamon Press, 1961.
4. Ewing, M. and Worzel, J.L.,  
"Long-Range Sound Transmission", Geological Society of America, Mem. 27, 1948.
5. Frosch, R.A.  
"Underwater Sound: Deep Ocean Propagation," Science, Vol. 146, pp. 889 - 894, 1964.
6. Frosch, R.A., Klerer, M., and Tyson, L.  
"Long-Range Localization of Small Underwater Charges," JASA, Vol. 33, pp. 1804 - 1805, 1961.
7. Fuglister, F.C.  
Atlantic Ocean Atlas, Woods Hole, Massachusetts, Woods Hole Oceanographic Institution, 1960.
8. Haurwitz, B., Stommel, H., and Munk, W.H.  
"On the Thermal Unrest in the Ocean", Rossby Memorial Volume, Rockefeller Institute Press, New York, 1959.
9. Knauss, J.A.  
"Observations of Internal Waves of Tidal Period Made with Neutrally Buoyant Floats," JMR, Vol. 20, #2, pp. 111 - 118, 1962.

10. Pochapsky, T.E.

"Measurements of Deep Water Movements with Instrumented Neutrally Buoyant Floats," JGR, Vol. 71, #10, pp. 2491 - 2504, 1966.

11. -----

"Measurements of Small-Scale Oceanic Motions with Neutrally Buoyant Floats," Tellus, Vol. 15, pp. 352 - 362, 1963.

12. Schroeder, E., Stommel, H., Menzel, D., and Sutcliffe, W.

"Climatic Stability of 18°C Water at Bermuda," JGR, Vol. 64, #3, pp. 363 - 366, 1959.

13. Swallow, J.C.

"A Neutral-Buoyancy Float for Measuring Deep Current", DSR, Vol. 3, pp. 74 - 81, 1955.